A study of the adequacy of quasi-geostrophic dynamics for modeling the effect of frontal cyclones on the larger scale flow

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This period of the grant research effort covered the second half of my sabbatical leave at the Department of Atmospheric Science, State University of New York at Albany (SUNYA). As was the case during the period September through December 1984, the department chairman, Dr. Richard Orville, graciously provided me with computer funds, as well as a terminal for my work. Hence, no charge to NASA was made for any of the computing carried out during my sabbatical leave. Due to this, I requested and received a 9 month, no cost extension to this grant for use of computer funds (see Future Plans). I returned to Missouri at the end of June.

Research Objectives:

The major objectives of the study are summarized as follows:

1. To test the validity of quasi-geostrophic (QG) dynamics, compared to primitive equation (PE) dynamics, for modeling the effect of cyclone waves on the larger scale flow, and
2. To study the formation of frontal cyclones and the dynamics of occluded frontogenesis.

These objectives remain the same as in the previous progress report (July - December 1984). The work described in this report is a continuation of that discussed in the previous report.

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Significant Accomplishments:

A) Simulation of polar lows. The work on simulation of polar lows has continued along two lines, as is now described.

1) Surface friction runs with the PE model and the wavelength of maximum instability.

The zonally independent basic state used for the polar low study, when analyzed with a linear, frictionless, 2-dimensional, finite-difference, QG model to reveal the structure and growth rate of the fastest growing normal modes as a function of channel length, yielded a growth rate versus channel length curve presented in the previous report and included here as Fig. 1. PE model runs, with no friction, for 700 and 1200 km were made and the growth rates for the linear phase of growth are on Fig. 1 (PE, NF X's).

Surface friction was added to the lowest level only of the PE model in the form of a drag coefficient and proportional to the velocity squared. Runs were made for 700 to 1200 km channel lengths and the growth rates, for the linear phase of growth, appear on Fig. 1 (PE, F X's). Adding surface friction is seen to reduce the growth rates, with the 700 km growth rate being reduced more than the 1200 km growth rate. Yet even with friction, the 700 km growth rate is greater than the 1200 km growth rate and no wavelength (channel length) of maximum instability is found above 700 km. The results suggest that, with or without friction, the shorter the zonal wavelength of an initially small disturbance, the faster it will grow, given this particular basic state (described in the previous progress report).

Since the normal modes become more shallow as the channel length decreases, it is probable that the limited vertical resolution in all the models (10 levels) may cause significant error and hence the growth rate curve may become increasingly inaccurate with decreasing channel length. The

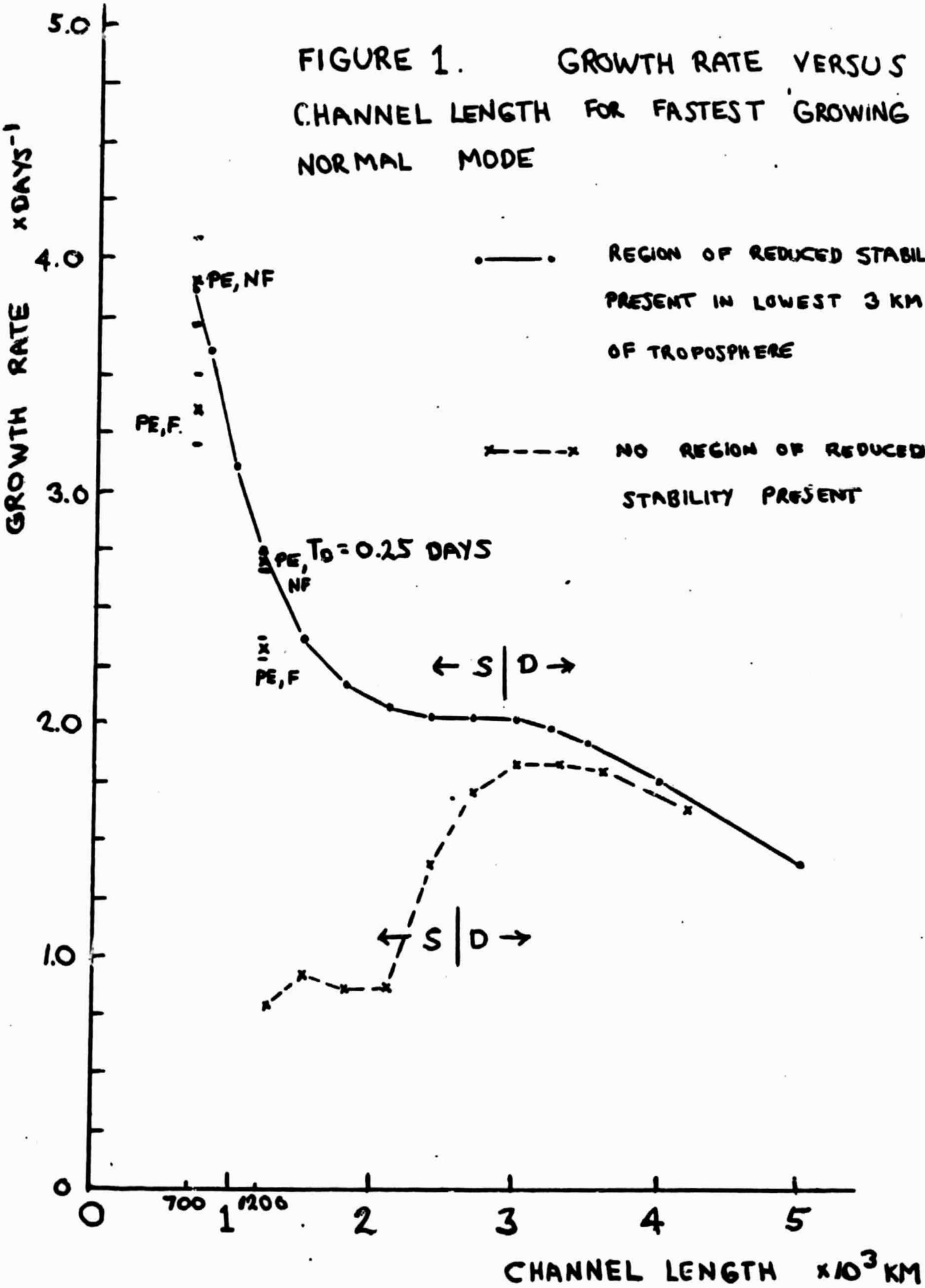

FIGURE 1. GROWTH RATE VERSUS CHANNEL LENGTH FOR FASTEST GROWING NORMAL MODE

lack of a wavelength of maximum instability above 700 km may be an artifice of the limited vertical resolution.

The exact shape of the curve and the question of where (or if) a wavelength of maximum instability exists probably will not be investigated further. Since the exact curve depends on details of the shape of the basic state jet and on details of the static stability profile used, as well as on the vertical and horizontal resolution of the linear QG model, and since the basic state chosen is only meant to be a simplified idealization of the atmospheric region within which polar lows develop, there seems to be no need to pursue further the precise shape of the growth rate curve. The purpose of the linear analysis was to show that the addition of a region of reduced stability to the lowest 3 km of the basic state would cause short wavelength normal modes to grow rapidly. (This feature of the basic state simulates the destabilization of the lower troposphere as cold air flows equatorward over warmer ocean or land, conditions within which polar lows develop. Comparison of the two curves in Fig. 1 shows this to be the case. For channel lengths (and hence wavelengths) around 1000 km, normal modes have significantly enhanced growth rates if the region of reduced stability is present in the lower troposphere. These wavelengths and growth rates are similar to those of observed polar lows (Sardie and Warner, 1983).

2) Fine resolution PE simulation of a polar low.

As described in the previous progress report, coarse resolution, frictionless PE and QG integrations ($\Delta X, \Delta Y$ = 100 km) were made, utilizing the "polar low" basic state with a 1200 km channel length. Similarities between the PE and observed polar lows were described in that report. A second "1200 km" PE run with surface friction and $\Delta X, \Delta Y$ = 100 km was made (described above in this report); it extended in time over the life cycle of the simulated polar low and was compared to the frictionless PE run. Further improvements in realism resulted from the presence of friction.

Based upon this second PE integration, a fine-resolution PE run with friction was made, within which $\Delta X, \Delta Y$ = 50 km. The vertical resolution remained at 10 levels. The channel width was reduced from 3600 to 2400 km in order to reduce computing requirements; the 2400 km width was more than adequate as no problems developed near the channel walls. This 1200 km length, 2400 km width still required 26 x 50 x 10 = 13,000 gridpoints, as well as a 2½ minute timestep, a large computing job compared to my usual requirements. The results were similar to but more realistic than those of the coarse resolution PE runs.

The similarities of this fine resolution run to observed polar low development are described well by what appeared in the previous progress report. Fig. 2 shows the raw pressure and temperature patterns for day 1 of the integration, at the lowest vertical level (corresponding to near the earth's surface). At the time the total eddy kinetic energy had reached its maximum value, the central pressure had reached almost its mininum value and frontal evolution changed little from this time. This can be contrasted with Fig. 3, showing the pressure and temperature at the lowest vertical level for a PE friction integration at a similar stage of development (day 4) in the evolution of a much larger scale cyclone wave (3600 km channel length, 4200 km width, $\Delta X, \Delta Y$ = 150 km).

As described in the previous progress report and as seen by comparing Figs. 2 and 3, the 1200 km polar low and the larger cyclone wave simulations differ in that the polar low simulation a) shows a small ($\sim$500 km across) vortex in contrast to the large vortex dominating the channel in Fig. 3, b) shows only a broad, weak pressure ridge but not a distinct "high" as

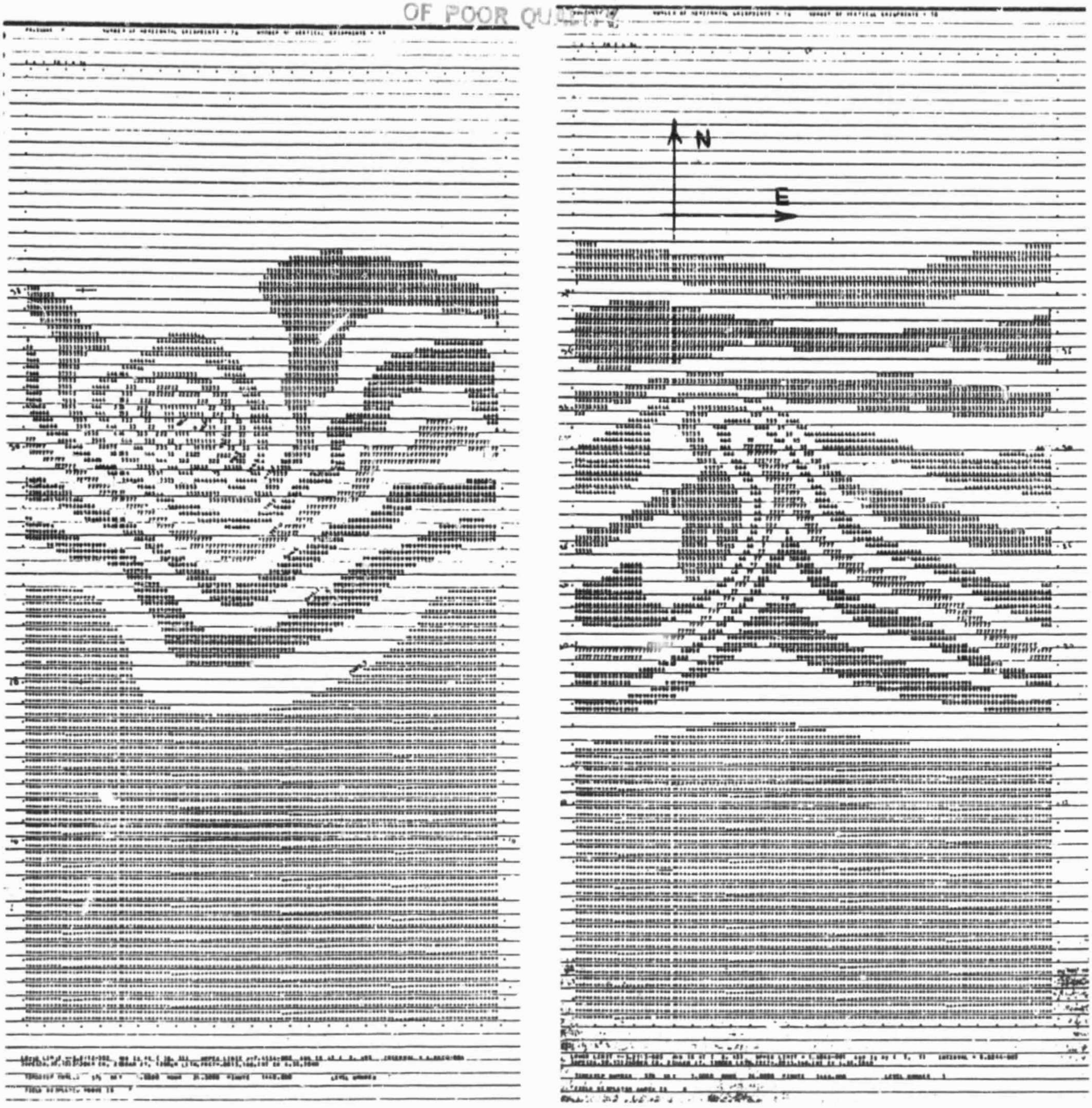

Fig. 2. Raw printer output from fine resolution polar low simulation. Pressure (left) and temperature (right), Day 1, lowest vertical level. Domain is 1200 km by 2400 km, cyclic E-W boundary conditions. $\Delta x = \Delta y = 50$ km.

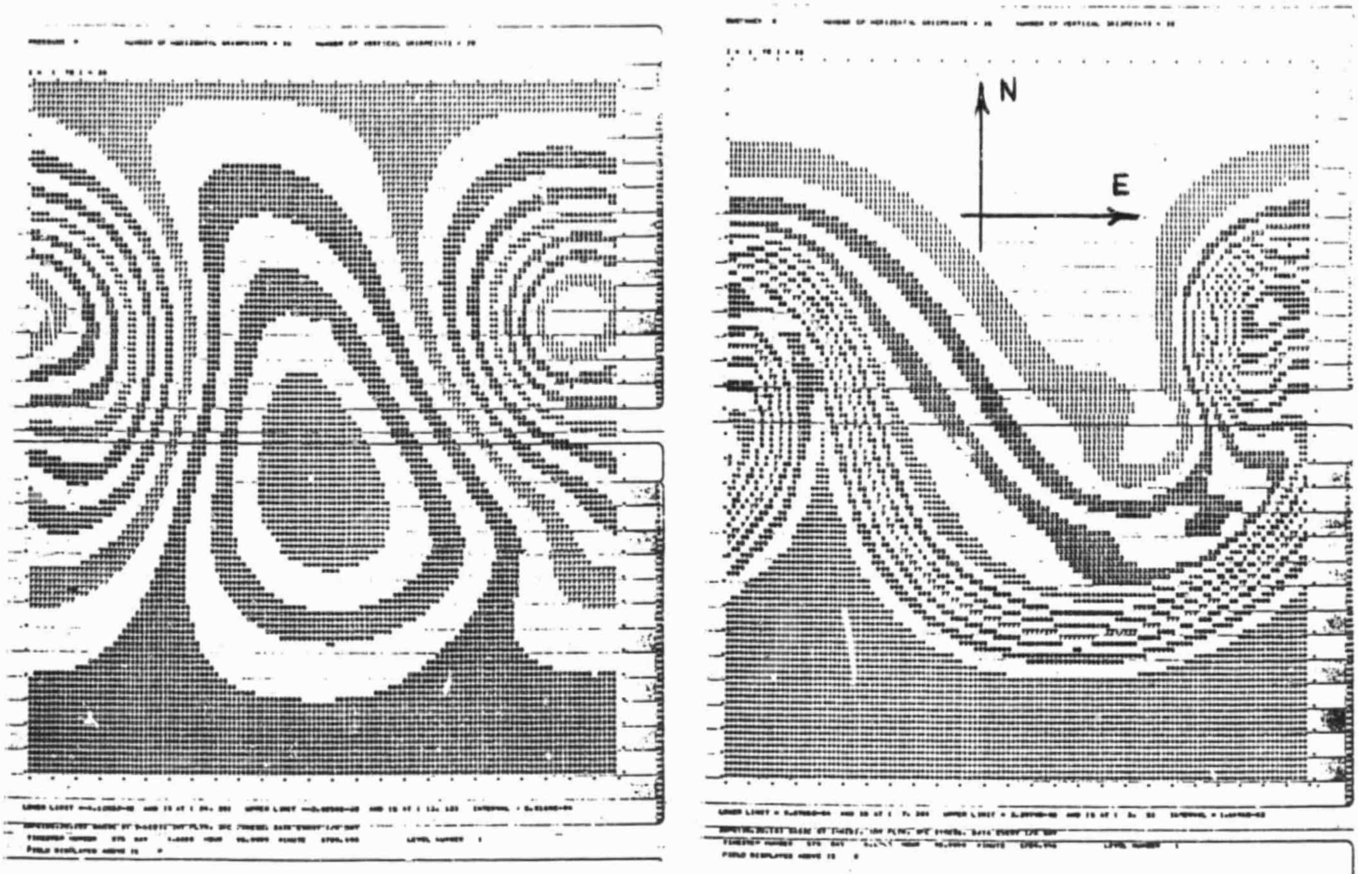

Fig. 3. Raw printer output from larger scale baroclinic wave evolution. Pressure (left) and temperature (right), Day 4, lowest vertical level. Domain is 3600 km by 4200 km, cyclic E-W boundary conditions. $\Delta x = \Delta y = 150$ km. Note: This is not to same scale as is Fig. 2.

appears in Fig. 3 and c) shows a long cold front with a short warm frontal region, in contrast to long, strong cold and warm fronts in Fig. 3. In all these ways the polar low simulation of Fig. 2 is more like the structure of observed polar lows (see Locatelli, et al, 1982) than is the larger scale cyclonic wave simulation of Fig. 3.

The warm front formed first in the polar low simulation, becoming apparent by day 1/2, while the cold front formed quite quickly, between day 1/2 and 3/4. Both fronts formed in locations close to where they appear in Fig. 2 and more or less remained in those positions, forming an "in situ" occlusion. These fronts were quite strong due to the 50 km resolution of the integration.

The fine resolution run also produced significant deepening of the disturbance amplitude at channel mid-levels, corresponding to 500-300 mb, as described in the previous progress report.

Data were recorded for 3 hour intervals on the tape taken to UMC from SUNYA. They hopefully will allow trajectory calculations to be made for motions in the region of the "occluded front" seen in Fig. 2.

The above work was described in five meetings and seminars I attended:

- paper presented at the Fifth Conference on Atmospheric and Oceanic Waves and Stability, sponsored by the American Meteorological Society at New Orleans, La., March 4-7, 1985.
- seminar presented at the Department of Atmospheric Science, SUNYA, April 15, 1985.
- seminar presented at the Laboratory for Atmospheres, Goddard Space Flight Center, NASA, Greenbelt, Md., April 25, 1985.

- seminar presented at Atmospheric and Environmental Research, Inc., Cambridge, Mass., May 23, 1985.
- paper presented at the panel review of the NASA Global Scale Atmospheric Processes Research Program sponsored by NASA headquarters, Columbia, Md., July 8-12, 1985.

B) "2-wave" initial state integrations.

Based on discussions with Professor Lance Bosart of the Department of Atmospheric Science, SUNYA, I decided to try to model the upper tropospheric interaction of a short wave moving through a long wave. I could then model a jet streak (associated with a short wave trough) as it propagates downstream from the long wave ridge and around the long wave trough. Such situations seem to be associated with upper level frontogenesis (see Keyser and Pecnick, 1985, p. 1260, for example).

I decided to model this situation by adding two perturbations to a zonally independent basic state, both normal mode solutions found as previously described. The first perturbation (the long wave) had a wavelength equal to the channel length; the second (the short wave) had a wavelength equal to half the channel length (so two short waves are present initially). Waves 1 and 2 were added to the basic state in this manner. No "initial balancing" was included in these runs, as was done in previous PE cases.

A basic state, different than the "polar low" basic state discussed previously, needed to be chosen so that the following criteria were satisfied:

1) the short waves would grow more rapidly than the long wave,
2) the short waves would propagate eastward more rapidly than the long wave and

3) Both long and short wave disturbance amplitudes would be relatively "deep," i.e., they would possess large disturbance amplitudes at jet stream level.

The third criterion hopefully allows deep surface frontal zones to form and favors more vigorous upper tropospheric activity including frontogenesis.

After several modifications, a basic state was found that produced satisfactory results. The channel length was chosen to be 5200 km (so waves 1 and 2 possessed 5200 km and 2600 km wavelengths, respectively), the width 6066 2/3 km; with 26 gridpoints E-W and 30 N-S the grid resolution $\Delta X, \Delta Y$ = 216 2/3 km, a coarse resolution, especially compared to the polar low simulations. Again 10 vertical levels were present.

Both perturbations were superimposed, with small amplitudes, on the zonally independent basic state: the maximum N-S perturbation wind component was set to be 10% of the maximum zonal basic state wind value. The initially small perturbation amplitudes allow the early growth and movement of the waves to be compared to linear theory. Several PE runs were made, with the short waves initially located at different places relative to the long wave. A long wave run, without short waves, was also made. All runs had surface friction. In addition, a 20% initial amplitude, no friction PE run was made.

The results of these runs appear to be quite interesting. They were made shortly before I left SUNYA at the conclusion of my visit; consequently little analysis has yet been done. Preliminary results include the following:

1) Upper-level frontogenesis seems to be occurring. A comparison of the 2 wave runs with the wave 1 only run should shed light on the role of the short wave in this process.

2) Varying the initial location of the short waves and hence the associated jet streaks, relative to the long wave, makes a major difference in subsequent development.

3) After day 7 in one of the 2 wave integrations, as a jet streak propagates through the long wave trough, a surface "low" forms on a pre-existing cold front, itself having formed as a result of earlier cyclone development. This low evolves into a mature cyclone; as it does so the front deforms and occludes. Thus the integration simulates a polar front cyclone with attendant occluded frontogenesis. This is the first polar front cyclone produced during work performed for this grant.

C) Conversion of SUNYA data for use at UMC.

The last significant achievement was the conversion of all the data generated by the SUNYA integrations, as well as the FORTRAN source programs written there, into a form readable on the UMC computer system. This required several weeks of programming effort, including testing the procedures as much as was practically possible.

Current Research:

Data tapes are being generated at UMC from the SUNYA data tapes. This will enable the data analysis programs written at UMC to access the SUNYA data as if they had been generated at UMC. Creation of one UMC archive type containing all 9 major integrations made at SUNYA, both PE and QG, is the goal of this work. In addition, data analysis programs written at SUNYA will be incorporated into the UMC programs.

Analysis is being carried out on the fine resolution polar low simulation data, the goal being to complete a paper, tentatively titled "Simulation of a polar low using a dry primitive equations model."

Future Plans:

In the previous progress report, under this section, I indicated a plan to add a surface frontal zone to the basic state, with the hope of simulating a "polar front cyclone." As discussed above, one of the "2-wave" runs did just that. I therefore plan to run parallel PE and QG integrations beginning with day 7 data from the 2 wave run. This will compare the effect of PE versus QG dynamics for the frontal cyclone evolution. Zonal and time averaged PE and QG eddy fluxes will be compared. This PE versus QG frontal cyclone comparison will provide an important case for objective 1) of this study, as well as for objective 2).

The development of the occluded front within evolving cyclones will be studied. The fine resolution polar low case and the 2-wave "frontal cyclone" case provide 2 situations within which "occluded fronts" seem to have formed, and I plan to analyze both cases in order to study this. Other, earlier PE runs will also be examined. A trajectory program will be written for this work.

A 9 month-no cost extension for use of the grant monies for computing and publication was requested and granted. This will allow use of the funds through September 1986. The request was made because virtually none of the computing funds were used while I was on sabbatical leave, funds having been provided to me for computing by the Department of Atmospheric Science, SUNYA.

References:

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Locatelli, J. D., P. V. Hobbs and J. A. Werth, 1982: Mesoscale structure of vortices in polar air streams. Mon. Wea. Rev., 110, 1417-1433.

Sardie, J. M. and T. T. Warner, 1983: On the mechanism for the development of polar lows. J. Atmos. Sci., 40, 869-881.